Digital Data Signal Space Diagrams

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Signal space diagrams are described which show the pattern of amplitude and phase variation for several kinds of modulated carrier signals commonly used in digital data transmission. Such diagrams illustrate important similarities and differences among the various modulation methods. Oscilloscope pictures of actual data signal patterns are presented, and it is shown that these patterns can be used to detect the presence of amplitude and delay distortions in the transmission channel.

I. INTRODUCTION

Many different kinds of modulated carrier signals are being used in digital communication systems. All these various data signals can be expressed in the general form $A(t) \cos [\omega_c t + \phi(t)]$ where a carrier $\cos \omega_c t$ is varied in amplitude by $A(t)$ and in phase by $\phi(t)$. The various modulation methods impart different patterns of amplitude and phase variation. The characteristic pattern of a given modulation method can be portrayed by a polar plot of A and ϕ in which the angular reference is $\omega_c t$. This type of plot will be referred to as a "signal space diagram."

Signal space diagrams will be described for several kinds of carrier modulation. Only synchronous signals consisting of sequences of evenly spaced symbols will be considered. In each case the received symbols can be thought of as a sequence of carrier pulses or bursts, each with an envelope shape determined by the channel characteristic. In such a view the differences among the types of modulation are due to the number of pulse amplitudes and phases which are used, the particular phase sequences used, and the spacing between pulses. In order to obtain the simplest signal space diagram it is desirable to choose the reference ω_c as the center of the received pulse spectrum so that the phase variation of a single isolated pulse will be minimized. With a symmetrical pulse spectrum and a linear phase characteristic this reduces the pattern of a single isolated pulse to a radial line. When the phase of the carrier varies from pulse to pulse and the pulses overlap, more complicated

patterns are formed. By transmitting a random sequence, a pattern of all the permitted amplitude and phase variations of that particular type of modulation is obtained.

Space diagrams will be presented for a number of commonly used data signals. In these examples the pulse envelope has been taken to have a raised-cosine shape in time in order to make the diagrams consist of circles and straight lines. This is a close approximation to the case of a raised-cosine pulse spectrum which is often typical in actual data systems. The pulse spacing, T, for the double-sideband examples is equal to the reciprocal of the half-amplitude width of the pulse spectrum. This corresponds to the maximum rate which avoids intersymbol interference as described by Nyquist. Pulse spacings of $T/2$ are used in FM and VSB methods where special conditions are established to avoid intersymbol interference.

II. SIGNAL SPACE DIAGRAMS FOR VARIOUS TYPES OF MODULATION

2.1 *Amplitude Modulation*

The first example is for on-off AM where mark is represented by a pulse and space by no pulse. The carrier phase remains the same from pulse to pulse, thus resulting in a straight-line pattern as shown in Fig. 1. The signal positions at the mid-symbol sampling instants are indicated by points M and S which are separated by the pulse amplitude A. The shape of the pulses is indicated at the right in the figure.

The diagram for suppressed-carrier AM or two-phase signals is shown in Fig. 2. In this case a pulse is sent for both mark and space, but the carrier phase for space is opposite to that for mark. Again the diagram is a straight line, but the mark and space sampling points are separated

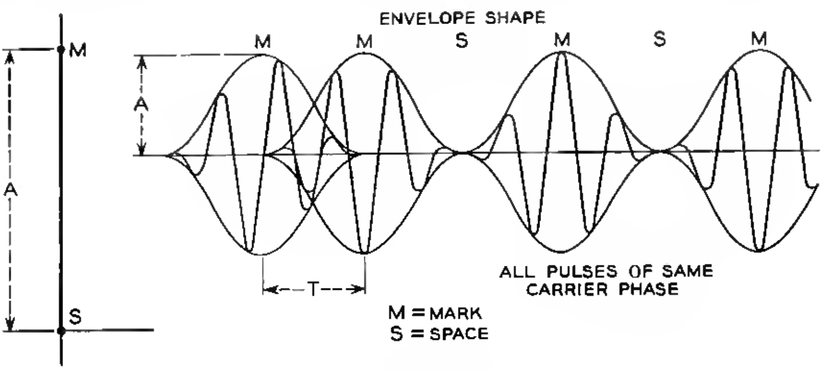

Fig. 1 — On-off AM.

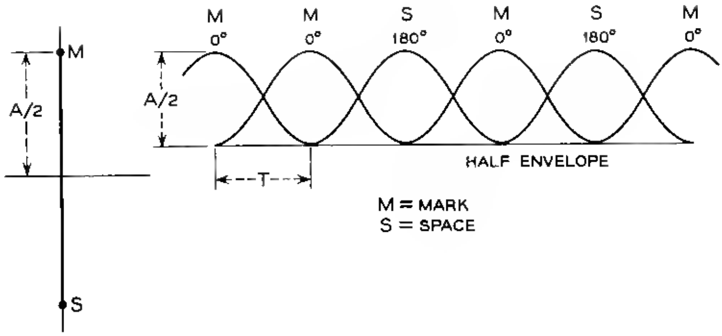

Fig. 2 — Suppressed-carrier AM or binary PM with 0° and 180° changes.

by twice the distance of the pulse amplitude. The positive half of the envelope and the carrier phase for each pulse are indicated at the right. A minimum separation of A is obtained with a pulse amplitude of $A/2$. As compared with the on-off case of Fig. 1, the same margin against noise is obtained with 3 db less average power and 6 db less peak power.

2.2 *Phase Modulation*

Binary phase modulation where the choice of phase change is 0° or 180° results in the diagram of Fig. 2, as noted above. Alternatively, the choice of phase change can be ±90°. This has the advantage of symmetry and less amplitude variation. The diagram for this type of signal is a square, as shown in Fig. 3. The signal can move in either direction around the square and at the centers of the symbols is at one of the corners. Since there is always a 90° change between symbols, the signal alternates between corners marked with dots and those marked with circles. For a peak signal of $A/2$ there is a minimum separation between dot positions or circle positions of A, as was the case in Fig. 2.

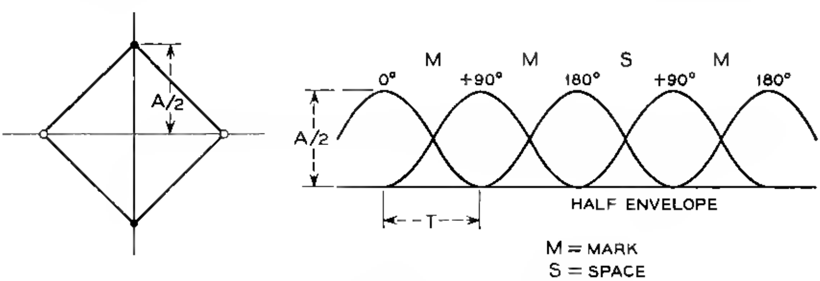

Fig. 3 — Binary PM with ±90° changes.

Note that the separation of interest is that between alternative choices for a given pulse rather than that between successive pulses.

Diagrams for two cases of quaternary phase modulation are presented. When the phase change between symbols is 0°, ±90° or 180° the diagram is a square with diagonals as shown in Fig. 4. The signal can progress around the square in either direction, go across a diagonal or remain at one corner with no restrictions. The four possible positions at the centers of the symbols are indicated by dots. For a minimum separation, A, between states the pulse peak becomes $A/\sqrt{2}$. This indicates that for this quaternary system to have the same noise margin per decision as the two-phase signal of Fig. 2 the power must be increased 3 db. This type of signal is equivalent to the sum of two AM suppressed-carrier signals at quadrature phase.

When phase changes of ±45° or ±135° are used between symbols there are eight possible phases for the pulses. The possible positions of the signal vector at the symbol centers are shown as dots and small circles on the diagram of Fig. 5. There is always a phase change between symbols, and the signal must alternate between dot positions and circle positions. With a peak pulse amplitude of $A/\sqrt{2}$ the minimum separation between dots or between circles is again A, as in the previous case.

2.3 *Vestigial Sideband*

It is assumed that the pulse spectrum for vestigial sideband has the same raised cosine shape used in the previous examples. It is also assumed that the pulse rate is twice the Nyquist rate for double-sideband operation and that the pulses originate from the modulation of a suppressed carrier higher in frequency than midband by an amount equal to one quarter of the pulse rate, as indicated in Fig. 6. This results in a phase change between adjacent pulses of ±90°. As shown in Fig. 6, the pulses overlap to the extent that at the peak of one pulse the adjacent pulses

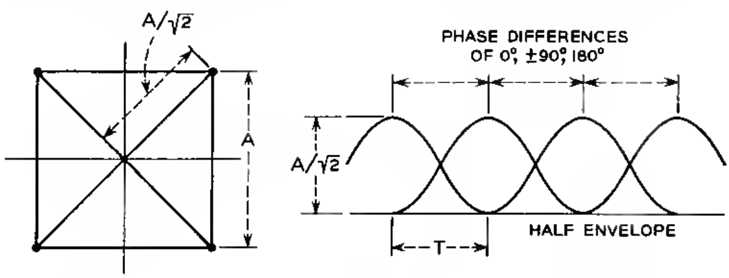

Fig. 4 — Quadrature AM or PM with 0°, ±90°, or 180° changes.

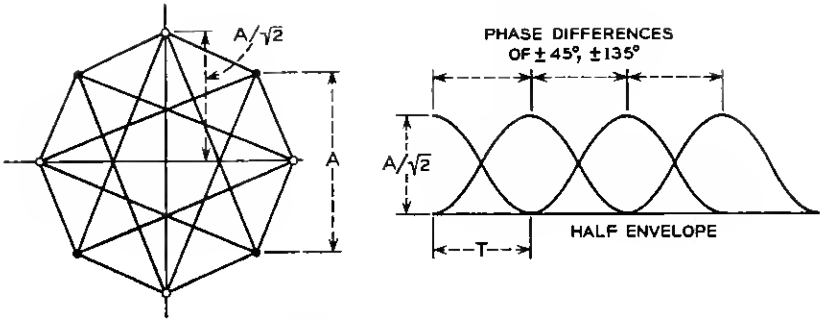

Fig. 5 — PM with ±45° or ±135° changes.

are each at half amplitude. This severe interference is at quadrature phase to the wanted pulse and is eliminated by the use of coherent detection. The signal phase at the center of a symbol is not affected if the two adjacent pulses are of opposing quadrature phases but is perturbed ±45° if the adjacent pulses are of the same quadrature phase. For example, on the diagram of Fig. 6 the center of a marking symbol can occur at any of the three dot positions at the top of the diagram de-

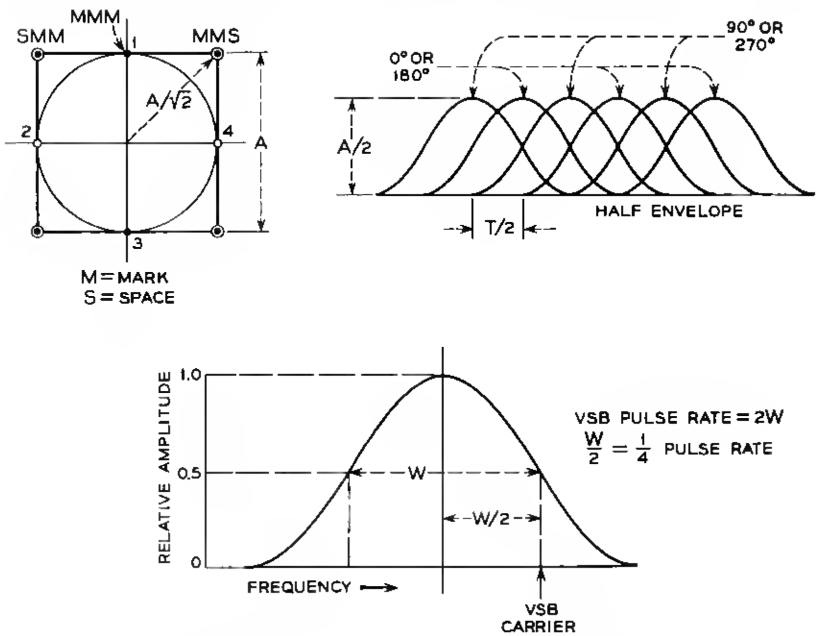

Fig. 6 — VSB: raised cosine pulse spectrum showing location of VSB carrier.

pending on the adjacent symbols as indicated. The phase of the coherent carrier used for detection advances around the diagram by 90° each symbol in the point sequence 1, 2, 3, 4. A continuous marking signal consequently follows this same sequence. A continuous spacing signal likewise advances 90° during each symbol but remains opposite in phase to the coherent reference.

For continuous mark-space alternations each symbol pulse is retarded by 90° from the preceding pulse, and the signal moves around the circle in the opposite direction from steady mark or space. The signal always alternates between dot and small circle points. The corners of the square portion of the diagram are both dot and circle points, and the signal may rest at such a point continuously and represent a MMSSMMSS sequence. All changes in direction of rotation about the diagram occur at the corners of the square; otherwise, the only restriction is for the alternation of the dot and small circle positions. Here again, with a peak signal of $A/\sqrt{2}$, a minimum separation of A between mark and space dots or mark and space circles is obtained. Thus the speed is doubled at a cost of 3 db more power, as in the case of quaternary phase modulation. Note that the individual pulse amplitudes are $A/2$, as for the two-phase case, but that the pulse spacing is halved. For vestigial sideband operation these pulses are sent serially, while for the quaternary phase case of Fig. 4 the pulses can be considered to be of amplitude $A/2$ sent two at a time.

2.4 *Frequency Modulation*

The binary rectangular wave frequency modulation case to be presented here is the ideal one where the bit rate is equal to the frequency shift between mark and space. For a continuous mark or space signal this results in the signal changing phase 180° between successive symbols. Again it is assumed that the signal is shaped to give a raised cosine pulse spectrum. Such an FM signal can be resolved into two components, a two-phase signal carrying the binary information and a quadrature component consisting of steady mark and space as indicated by the vector diagram of Fig. 7. This quadrature component can be considered to consist of alternating $\pm 90°$ carrier pulses located between the 0° and 180° pulses carrying the information. The diagram for such an FM signal is shown in Fig. 7. A continuous mark condition (lower frequency) causes the signal to move around the circle clockwise. A continuous space causes a counterclockwise rotation. At the center of the symbols the signal is at either point A or B. A frequency transition causes the signal to swing out to one of the points "x" and reverse the

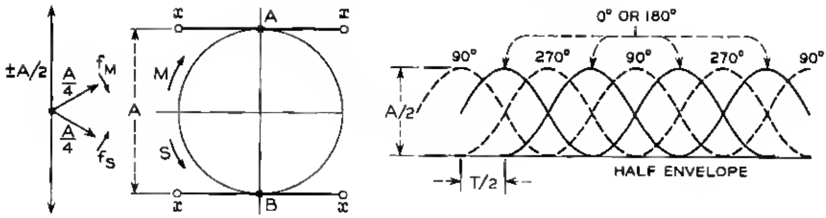

Fig. 7 — FM.

direction of rotation. For continuous reversals the signal swings back and forth through point A or B along a horizontal line. For such a sequence of reversals the phase swing is $\pm 45°$.

Although the steady mark and space frequency components which impart the horizontal component of motion in the diagram carry no information, they do permit the detection of the signal on a frequency basis. The mark and space conditions are indicated by the direction of rotation at points A and B. The quadrature component of the signal represents half of the total power. Consequently an FM signal requires twice the power of a two-phase signal to produce the same minimum separation of the points A and B. The two-phase component of the FM wave can be detected by a coherent carrier to determine whether the signal is at point A or B. It will be seen, however, that this leads to a polarity ambiguity because of the nature of the encoding. Reversals of either phase can be represented by the signal being at point A or at point B for successive symbols. A change from point A to point B indicates no transition of the information wave.

2.5 *Duobinary Frequency Modulation*[1]

The duobinary technique developed by Lender is a means of doubling the rate of sending binary information. The data are first differentially encoded so that a transition is made for a space symbol and no transition for a mark symbol. The resulting double-speed binary signal is then passed through a frequency shift channel of the type just described for ordinary binary operation with no change in frequency shift or channel shaping. The signal can change phase a maximum of $\pm 90°$ during these half-length intervals. This results in both the in-phase and quadrature pulses carrying information. The diagram of Fig. 7 applies in part, but because of the double rate we are interested in more points of the pattern. For instance, for steady mark the signal moves around the circle in either direction and the receiver samples the signal not only at points A and B but also at points C and D as shown in Fig. 8. The occurrence

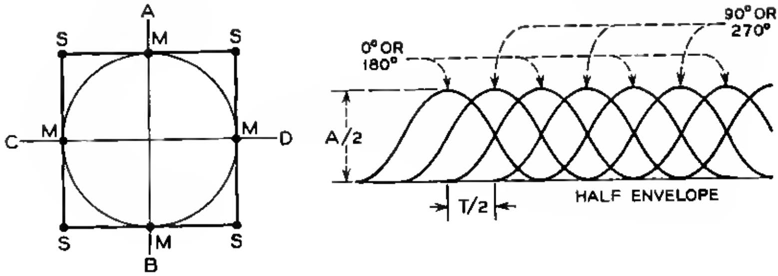

Fig. 8 — Duobinary FM.

of a space symbol causes a frequency transition and the signal leaves the circle and reverses direction at one of the points labeled S. If there are two successive space symbols causing two frequency transitions, the signal pauses at an S point for one symbol interval and then continues on in the same direction of rotation. An odd number of successive space symbols leads to a reversal of rotation while an even number does not. The signal can thus proceed around the circle clockwise or counter-clockwise or pause at one of the S points. The rotating conditions represent the high- and low-frequency states while the pausing represents the midband frequency. When the signal is detected on a frequency basis, a three-level baseband output is obtained, with the outer levels representing mark and the center level space.

The complete duobinary diagram of Fig. 8 is seen to be the same as that of Fig. 6 for a vestigial sideband signal. This indicates that the two kinds of line signals are of the same form although the encoding is different. Experimental verification of this identity has been demonstrated by transmitting a vestigial sideband signal to an FM receiver and obtaining a three-level baseband signal such as received in duobinary FM. Fig. 9 shows a photograph of the received eye pattern.

III. OSCILLOSCOPE PRESENTATION OF SIGNAL SPACE DIAGRAMS

Signal space diagrams of actual data signals can be displayed by coherently detecting both the in-phase and the quadrature components with respect to a midband reference frequency and applying them to the X and Y deflection circuits of an oscilloscope. Such an arrangement was constructed in the laboratory and used to obtain the signal pattern photographs shown in Fig. 10. Three kinds of signals are shown, (a) binary FM, (b) quaternary PM, (c) binary VSB. These were all voice-band data signals within a band centered near 1800 cps. Appropriate filters were used to shape the pulse spectrum closely to a raised cosine.

To appraise the possible value of such signal patterns as a measure of

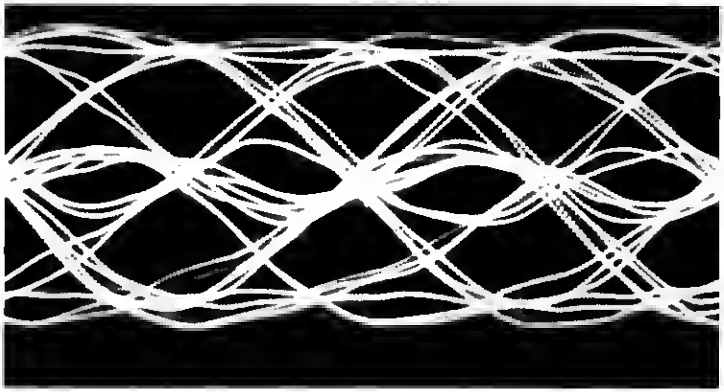

Fig. 9 — Oscilloscope picture of three-level eye obtained by receiving a VSB signal on a 202B FM receiver.

signal quality, the effects of amplitude slope and delay distortion were observed. Examples of the results are shown by the oscilloscope pictures of Fig. 11. The simulated line distortion characteristics which produced these patterns are given in Fig. 12. The effect of amplitude slope is readily apparent for FM and VSB, where portions of the transmitted sequence result in the signal resting at the high-loss end of the band. This accounts for the smaller inner circular portion of the patterns. In the case of PM the pattern is changed but not at the mid-symbol sampling points. The effect of high-end delay distortion shows up as a rotation of one part of the pattern with respect to others. This is readily seen in the PM examples, where the portion of the pattern formed by repeated phase advances is rotated with respect to the portion formed by repeated phase retardations.

IV. CONCLUDING REMARKS

Signal space diagrams have been described for a number of commonly used data signals. These diagrams are useful in comparing data signals

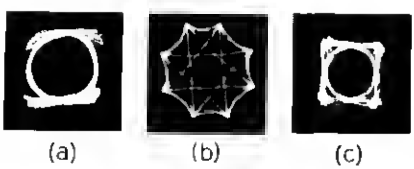

Fig. 10 — Oscilloscope pictures of signal space patterns for a 63-bit pseudo-random sequence: (a) binary FM, 1000 bits/sec, (b) quaternary PM, 2000 bits/sec, (c) binary VSB, 2400 bits/sec.

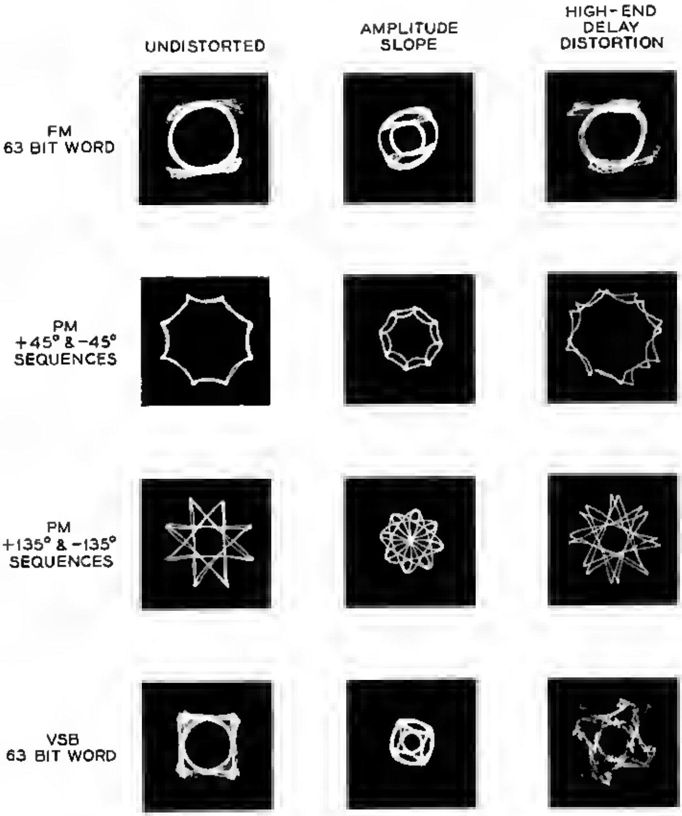

Fig. 11 — Oscilloscope pictures of signal space patterns showing effect of amplitude slope and envelope delay distortion.

on a common basis without regard to specific detection techniques. Similarities and differences are revealed which may not otherwise be apparent and various possible detection methods can be visualized. The margin against noise with ideal detection methods is also indicated by the spatial separation of the sampling points. The signal power is indicated by the pulse amplitude and repetition rate. For example, the foregoing diagrams illustrate that binary FM, quaternary PM and binary VSB signals all give the same margin against noise for a given transmitted power. The binary FM system, however, operates at half the speed of the other two for a given bandwidth. It has also been shown that a duobinary FM signal has the same pattern as a binary VSB signal. The relative simplicity afforded by FM detection of such a signal

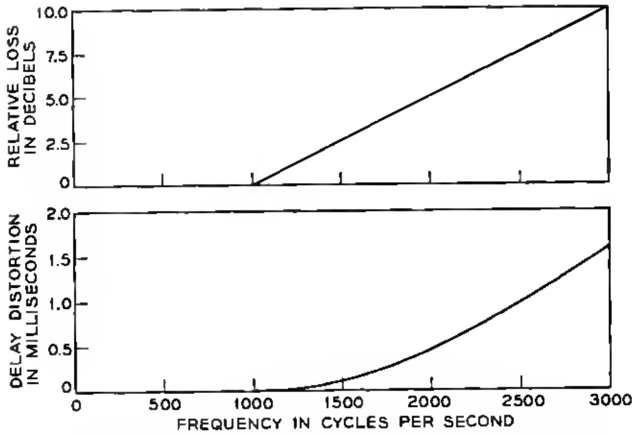

Fig. 12 — Amplitude and delay distortion characteristics used to distort the signal patterns shown in Fig. 11.

as against coherent detection is accomplished at a loss of approximately 6 db in margin against noise.

Considerable information about the nature of the channel characteristic is also indicated by the signal diagrams. The use of signal diagrams as an indication of signal quality is primarily limited, however, to the laboratory. The required synchronization with the midband frequency and symbol rate of the signals to be observed tends to make the method unsuitable for field measurements.

V. ACKNOWLEDGMENTS

The construction of circuitry for resolving data signals into quadrature components and the photography of the oscilloscope patterns were carried out by John Grason under the direction of F. K. Becker.

REFERENCE

1. Lender, A., The Duobinary Technique for High-Speed Data Transmission IEEE Trans. Comm. and Elect., **82,** May, 1963, pp. 214–218.